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LOFAR Scientific Memorandum #1: Cluster-Formation Synchrotron Radiation

A Contaminant for Epoch of Reionization Experiments and a Signal for Probing Cluster Formation and the γ-ray Background

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14. ABSTRACT

The process of assembly of the largest clusters of galaxies, $M \gtrsim 10^{14}\,M_{\odot}$, should have produced shocks that accelerated electrons to TeV energies. In turn, these electrons will produce synchrotron emission. A recent analysis by Waxman and Loeb predicts that this intergalactic synchrotron background will have an amplitude of order 10 K and characteristic fluctuation size of 0.1°–1° at frequencies near 100 MHz. This cluster-formation synchrotron radiation can be targeted in LOFAR and SKA observations as a source of information on cluster formation that will complement detailed gamma-ray studies. Existing low-frequency VLA observations already have detected what are probably the brightest examples of such cluster-formation synchrotron radiation. Conversely, the predicted amplitude of the cluster-formation synchrotron radiation is roughly 100 times larger than that predicted for the signature of the epoch of reionization in the (redshifted) H I line, but the angular scales are comparable. We suggest two strategies that may, singly or in combination, suffice to remove this contaminant from experiments designed to detect or map the H I signature of the EoR. Either strategy is demanding, though, as the accuracies required are probably 1 part in 5000 or better.

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CONTENTS

EXECUTIVE SUMMARY

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1. INTRODUCTION

The largest and most massive structures in the Universe are clusters of galaxies. In current models their formation proceeds from the conglomeration of smaller groups of galaxies. For particularly massive clusters, $M \gtrsim 10^{14}$ $M_{\odot}$, the formation should be accompanied by the generation of strong shocks. Observational support for this scenario is indicated by cluster halos and cluster relics. Particularly compelling in this regard are clusters, like Abell 754, in which on-going merger events are marked by both X-ray signatures and radio halos and relics (Kassim et al. 2001).

Based on the success of the 74 and 330 MHz systems on the VLA, observations of clusters of galaxies are recognized already to be a portion of the LOFAR Key Science Project: The Extragalactic Universe. A complementary LOFAR Key Science Project is the Epoch of Reionization experiment in which the signature of the collapse of the initial structures in the Universe is to be sought in the redshifted H I line.

The memorandum considers a recent analysis by Waxman & Loeb (2000) in which they assess the radio synchrotron emission produced during the formation of massive clusters. This cluster-formation synchrotron may prove to be both a rich signal as well as a potential foreground contaminent for the Epoch of Reionization Key Science Project. In §2 we summarize the analysis of Waxman & Loeb (2000) and their predictions for cluster-formation synchrotron radiation. In §3 we discuss how cluster formation may serve as a signal, particularly in concert with future gamma-ray instruments while in §4 we discuss its impact (as noise) on EoR experiments. In §5 we summarize our conclusions and recommendations. For definiteness we shall restrict the remainder of our discussion to LOFAR, but many of our conclusions apply also to the Square Kilometer Array (SKA).

2. STRUCTURE FORMATION

Loeb & Waxman (2000) have considered the implication of structure formation for particle acceleration (see also Keshet et al. 2002). Galactic supernova remnants are able to accelerate a small fraction of the post-shock electrons to TeV energies. Scaling supernova remnant shocks to intergalactic scales, Loeb & Waxman (2000) argue that the shocks created during structure formation should also accelerate electrons to TeV energies (see also Totani & Kitayama 2000; Kawasaki & Totani 2001).

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These highly relativistic electrons will cool by Compton scattering off the cosmic microwave backgroun (CMB). Loeb & Waxman (2000) demonstrate that, for nominal shock parameters, the inverse Compton scattered gamma rays may be the source of the diffuse extragalactic gamma-ray background. They obtain reasonable agreement of their model with the 30 MeV–100 GeV background observed by EGRET instrument on the Compton Gamma-Ray Observatory.

Waxman & Loeb (2000) extend this model to consider its impact on an intergalactic radio background. The highly relativistic electrons will cool via synchrotron radiation as well. To factors of order unity, they predict an rms brightness temperature fluctuation of

$$\sigma_{T_B} \sim 50\,\mathrm{K}\left(\frac{\nu}{100\,\mathrm{MHz}}\right)^{-3}, \tag{1}$$

on scales of 0°.1–1°. They focus on the possible implications of this intergalactic synchrotron emission on experiments designed to detect fluctuations in the CMB. They cite a number of CMB fluctuation experiments for which the sensitivities are beginning to approach this level.

3. MAPPING CLUSTER-FORMATION SYNCHROTRON RADIATION

Waxman & Loeb (2000) predict a significant correlation between γ-ray background and radio synchrotron fluctuations that is dominated by cluster halos at redshifts $z \lesssim 0.1$. Evaluation of the correlation translates into constraints on the strength and spatial distribution of intergalactic magnetic fields.

Waxman & Loeb (2000) predict that there should be roughly 10^2 clusters on the sky whose flux density exceeds 10 Jy, with larger numbers predicted for lower flux density estimates. Similar values have been obtained by T. Enßlin (2001, private communication). Observations with the 74 MHz system on the VLA have detected 3 cluster halos and/or relics (the Coma cluster, A2256, and A754). The current detection efficiency is near 100% as cluster halos or relics have been found in essentially all clusters observed in an effort to find such structures. Programs are being planned to conduct a less biased search for these structures, nonetheless, it seems reasonable to assume that VLA 74 MHz (and possibly 330 MHz) observations may detect many more cluster halos and relics. To date, we are not aware of any effort to compare the clusters detected at 74 MHz with unidentified EGRET sources.

By the time that LOFAR observations begin, the Gamma-ray Large Aperture Space Telescope (GLAST) should also be in orbit. With significantly better angular resolution than that of EGRET, comparison of sources detected with GLAST to those at other wavelengths should be significantly easier. If Waxman & Loeb (2000) are correct, detection of inverse Compton scattered gamma radiation and radio synchrotron radiation will be found to correlate. The gamma radiation depends upon the relativistic particle density (and the known CMB energy density) while the synchrotron radiation depends upon the relativistic particle density and the intra-cluster (or intergalactic) magnetic field strength. Thus comparison of LOFAR and GLAST images of massive clusters should be able to be combined to yield both the relativistic particle density and the magnetic field strength. In addition, because the dominant redshift is small, both kinds of fluctuations should correlate with the large-scale structure mapped out by galaxies in redshift surveys.

4. IMPLICATIONS FOR EPOCH OF REIONIZATION EXPERIMENTS

After the Universe recombined at $z \approx 1500$, it was largely neutral until the epoch of first star formation. Soon after the formation of the first stars, the Universe became reionized, probably on a fairly rapid time scale (e.g., Gnedin & Ostriker 1997). Recent observations of the $z = 6.28$ quasar SDSSp J103027.10+052455.0 suggest that the epoch of reionization (EoR) was complete at $z \simeq 6$ (Becker et al., 2001; Djorgovski et al. 2001).

The EoR should have two observational signatures at frequencies near 200 MHz due to redshifted H I line emission. First, the large decrease in the abundance of neutral hydrogen accompanying re-ionization should result in a sharp drop in the sky spectrum (Shaver et al. 1999). Second, there should be structures on angular scales of order $5'$ representing emission (or absorption) near ionization sources (Tozzi et al. 2000). Detecting these signatures will be challenging as the expected spectral decrement is about 1% of the amplitude of the CMB (and about 10^{-5} of the sky temperature due to the Galactic synchrotron radiation at these frequencies). Nonetheless, detection of the H I signature by either LOFAR or the SKA would be an important contribution in the study of the EoR. In particular, mapping the sky in the (redshifted) H I line would provide nearly full sky maps with either LOFAR or the SKA that could be analyzed for fluctuations. In contrast, studying absorption features in the spectra of distant quasars is limited to the available lines of sight to sufficiently distant quasars.

A key aspect of either detecting or mapping the EoR signatures is elimination of foreground emission. The expected amplitude of the H I signature is of order 10 mK, whereas even a cool part of the sky has a brightness temperature of order 100 K at these frequencies (Shaver et al. 1999). In pointing out that it might be possible to detect the EoR, Shaver et al. (1999) considered two foreground contaminants. The first is the Galactic synchrotron emission, and the second is foreground radio galaxies. They argued that by exploiting the relatively smooth spectra of these foreground sources, one could in principle remove them with sufficient accuracy to detect the EoR signature.

Moreover, the expected angular scales of these two foreground contaminants may assist in removing them from EoR observations. The structures in the H I line are predicted, relatively independent of the cosmological model, to have angular scales of order $1'$–$10'$. The Galactic synchrotron radiation has angular scales of $1°$ or larger (Haverkorn et al. 2001) and would be resolved out by interferometric observations. Radio galaxies and quasars should have angular scales of less than $1'$. Furthermore, the longer baselines of LOFAR or the SKA could be utilized to image a region of the sky and identify all of the radio sources above a flux density threshold. The contribution of these radio sources to the observed brightness temperature could then be subtracted.

At the frequencies of interest for detecting the highly redshifted H I line, Waxman & Loeb (2000) predict that the cluster-formation synchrotron radiation contributes an rms fluctuation amplitude of $\sigma_{T_B} \sim 3$ K (eqn. 1). In contrast to the other two contaminants discussed above, synchrotron emission from cluster assembly occurs on angular scales comparable to that expected for the EoR signature. We have not performed detailed simulations of EoR observations (nor for that matter did Loeb & Waxman or Waxman & Loeb, so the details of their predictions may be refined in the future). Nonetheless, it seems clear that a contaminant with an expected magnitude of 100 times that of the EoR signature is troubling.

First, the spectral signature of the synchrotron emission from cluster assembly should be smooth. Much like Galactic synchrotron emission, over the frequency range of interest, it should be sufficient to model the cluster assembly emission by a smooth power law or smooth spectrum with only modest curvature. In contrast, the EoR signature is thought to be limited to a few MHz.

Second, the cluster assembly emission should be dominated by the most massive clusters, those with $M \gtrsim 10^{14}$ $M_{\odot}$. Waxman & Loeb (2000) estimate that such clusters should cover no more than 10% of the sky. Thus, a possible *modus operandi* is to select a limited number of directions on the sky in which to try to detect or map the EoR signature. One could then image all of the clusters in these directions and subtract their contributions from the sky temperature.

We stress the relatively severe nature to which these corrections must be determined. The expected EoR signature is 10–50 mK. Thus, an accuracy of at least 1 part in 10^3, and probably closer to 1 part in 5000 or better, is required.

5. CONCLUSIONS

Models of structure formation predict that shocks in clusters of galaxies should also give rise to gamma-ray and radio emission. The former may have already been detected as the diffuse gamma-ray background. The latter is just at the limit of detectability at frequencies near 10 GHz.

This cluster-formation synchrotron radiation may prove to be a rich probe of the cluster formation process, particularly when combined with gamma-ray observations from future telescopes such as GLAST. Comparison of a cluster detected both by LOFAR and by GLAST should enable one to determine the relativistic particle density and magnetic field strength within the cluster.

The frequency dependence of the synchrotron emission from structure formation predicts that this emission could be problematic for attempts to detect the highly redshifted H I emission from the epoch of reionization. The amplitude of this foreground contaminant is estimated to be of order 3 K, and it would occur on angular scales of order $10'$. The amplitude is roughly 10^2 times larger than that predicted for the EoR signature, but the angular scales are comparable.

We suggest two strategies that may, singly or in combination, suffice to remove this contaminant. These strategies are modeled on those suggested already to deal with other foreground contaminants. One strategy is to exploit the (expected) smooth spectral nature of the structure formation emission. The other is to image the dominant sources of this emission and then subtract their contribution from the sky temperature.

Either strategy is demanding, though, as the accuracies required are probably 1 part in 5000 or better. Simulations, both of the structure formation process and the resulting emission as well as of the LOFAR sky and EoR detection experiments, would be valuable.

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